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14. ABSTRACT
The goal of this work is to increase our quantitative understanding of the partitioning of incident solar (shortwave) radiation by sea ice. The partitioning of shortwave radiation into components backscattered to the atmosphere, absorbed by the ice, and transmitted to the ocean is central to the ice-albedo feedback mechanism, the mean annual cycle of ice thickness, mechanical properties of the ice, and the quality and quantity of light available to under-ice biological communities. This partitioning is known to depend on the presence of surface scattering layers (SSLs). We conducted field observations and model simulations of radiative transfer within the surface layer and interior layers of sea ice. Results have been used to improve characterization of the properties of bare and ponded ice for the purpose of understanding the surface energy and mass balances of sea ice during summer. Three broad concepts have emerged from this work: (i) a 3-layer structure for specifying the vertical variation of optical properties of both bare and ponded sea ice, (ii) the optical properties found in the ice interior are independent of time, and (iii) a picture of the evolution of scattering near the surface of bare and ponded ice as the melt season progresses.

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Observing and Modeling the Surface Scattering Layer of First-Year Arctic Sea Ice

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LONG-TERM GOALS

The long-term goal of this work is to increase our quantitative understanding of the partitioning of incident solar (shortwave) radiation by sea ice. The partitioning of shortwave radiation into components backscattered to the atmosphere, absorbed by the ice, and transmitted to the ocean is central to the ice-albedo feedback mechanism, the mean annual cycle of ice thickness, mechanical properties of the ice, and the quality and quantity of light available to under-ice biological communities. This partitioning is known to depend strongly on the physical properties of the ice cover, including ice concentration, snow cover, depth and size of surface liquid water ponds, and the presence of surface scattering layers (SSLs). Despite the recognized importance of this partitioning, current sea-ice models generally do not include the detailed physics needed to describe how it depends on changes in ice properties. The focus of this research is to evaluate the impact of SSLs on the partitioning of incident solar radiation in the atmosphere-sea ice-ocean system.

OBJECTIVES

The overall objective of this work is to develop a conceptual model of how SSLs in melting first-year sea ice govern the partitioning of incident shortwave radiation in the ocean-ice-atmosphere system. This includes improving the physics employed in models that relate the physical and optical properties of sea ice.

To achieve this objective, we conducted field observations and model simulations of radiative transfer within the surface layer and interior layers of sea ice. Observations focus on (i) the evolution of SSLs, and (ii) how the physical properties of sea ice are related to the inherent optical properties (IOPs, e.g., absorption and scattering). Modeling efforts focus on defining relationships between the structural and optical properties of SSLs, which are typically drained and have low density and coarse grains. Results have been used to improve characterization of the properties of bare and ponded ice for the purpose of understanding the surface energy and mass balances of sea ice during summer.

Specific objectives include: (i) design and implementation of field equipment for measuring the spectral radiance transmitted through core samples of sea ice, (ii) acquisition of measurements of spectral transmission through sea ice during the onset and duration of the melt season, including drained and flooded bare ice, drained and flooded ponded ice, together with measurements of the physical properties (temperature, salinity and density) of each sample, (iii) calibration of the field measurements of spectral transmission to determine IOPs by combining optical modeling and

laboratory calibration measurements, and (iv) analysis and interpretation of the relationships between IOPs and physical properties to establish a conceptual model.

APPROACH

Our approach requires observations of the surface scattering layer on melting first-year summer sea ice as the layer forms and evolves. These observations were made in the field. A radiative transfer model was then used to interpret the optical observations and a "structural-optical" model was further developed to predict inherent optical properties from structural properties. IOPs include those optical properties which are fundamental to the ice: scattering and absorption coefficients and scattering phase functions. In general, IOPs are not directly observable in multiply scattering media. All radiative transfer models require knowledge of these IOPs, along with information about the domain geometry and incident light, to predict "apparent optical properties" (AOPs). AOPs are observable quantities, including albedo, transmittance, and total absorption. Inferred and predicted IOPs were compared so that the structural-optical model could be improved and tested.

A useful quantity known as the "similarity parameter" (s) was also employed. In this application, we took s to be the magnitude of the scattering coefficient (σ) multiplied by $(1- g)$, where g is the scattering asymmetry parameter. Use of this parameter as a bulk measure of the IOPs related to scattering has facilitated the analysis of the data. The process of integrating physical and optical data from the upper portions of the ice lead to our objective: a quantitative understanding of the role of the surface scattering layer in the optical properties of a summer ice cover.

WORK COMPLETED

Efforts during this project have focused on three tasks: (i) development and calibration of an optical core jacket, (ii) field deployment, and (iii) analysis of field data.

Development and calibration of optical core jacket

A unique tool was developed for making the measurements this project required. We call it an "optical core jacket" and it consists of a specialized core barrel coupled with optical sensors for measuring the amount of light transmitted through an ice core sample. Measurements made with the core jacket use a bootstrap approach. Once a core is removed from the ice, it is placed within the jacket. Coupled optical detectors are used to measure the transmitted spectral radiance T_λ of ambient diffuse incident radiation through the core. The top section of the segmented barrel is then removed (approximately 1 – 2 cm), the ice carefully sawed off, and another T_λ measurement made. This procedure of removing segments of the ice core and making sequential T_λ measurements yields a data set detailing the vertical structure of transmitted spectral radiance within the surface scattering layers and throughout the core. From these direct measurements of T_λ we estimate the IOPs using a two-dimensional Monte Carlo Radiative Transfer Model ("2DMCRT"; *Light et al.*, 2003) to correct for the effects of the jacket's optical properties and geometry. The model requires a prescribed vertical profile of the similarity parameter s. The simulated and observed values of T_λ are compared, and the profile of s is adjusted to produce a better match. When the match is deemed satisfactory, we have the desired profile of s that is consistent with the observations on the particular sample.

Calibration of the optical core jacket is necessary so that the correct properties can be supplied to the 2DMCRT. Some elements of the calibration were carried out in the laboratory and some in the field. In particular, 4 features needed to be calibrated: (i) the effective field-of-view of the fiber optic cables that

were used to collect light at the base of the jacket and deliver it to the spectrophotometer, (ii) the absorbing properties of the acrylic floor used in the jacket to support the core sample, (iii) the scattering properties of the opal glass diffuser plate at the top of the jacket, and (iv) the optical properties of the interior walls of the jacket cylinder. Experiments were carried out in the laboratory to estimate (i), (ii), and (iii). Item (iv) was calibrated in the field, where measurements of T_λ were made for three dilutions of latex calibration spheres (Duke Scientific). Observed values of T_λ for the three concentrations of spheres were compared with a LUT of 2DMCRT model predicted T_λ values using scattering parameters for the spheres derived from Mie theory. In this case, the profile of *s* is known a priori and the properties of the interior walls are adjusted to fit the measured T_λ.

Field deployment

Field measurements were made between 17 May and 23 June 2005. This interval extended from the beginning of the melt season through establishment of widespread surface ponding, when access to the ice became impractical. Ice cores were sampled and optical measurements made on 31 different days. By making measurements in the jacket quickly at the coring site, the amount of brine drainage from samples was limited. The sampling included time series of specific ice types: snow covered ice, ice cleared of snow, bare melting ice, and ponded ice. We also carried out studies to assess the repeatability and the spatial variability of the measurements.

Data collection procedures were as follows. First, a measurement of spectral albedo was taken at each study site prior to trampling or coring. Spectral albedo data are particularly useful for analyzing the core jacket data in the uppermost sections of the ice. Two coring locations were typically identified. Early in the season, snow covered and snow free cores were obtained, later in the season, bare and ponded ice cores were obtained. Initially, the uppermost 15 to 35 cm of each core was placed in the jacket. This permitted the surface layers to be sliced off with the highest vertical spatial resolution practical. This approach has yielded a highly resolved vertical profile of the IOPs within the uppermost 15 – 35 cm of the ice. Subsequently, 13 cm thick sections were measured from interior portions of the core sample.

The base of the core jacket was constructed to be watertight, permitting the sample to be flooded with either pond water or sea water, as appropriate. Typically the water drained immediately from those cores extracted from ponds. Measurements were made on both drained and re-flooded samples. Cores extracted from below-freeboard bare ice tended to drain more slowly, but this arrangement made it possible to re-flood those samples as well. The flooded samples represent our best approximation to in-situ conditions.

Analysis of data

All of the transmittance spectra that were collected have been catalogued. Spectra taken on the 13cm and 4cm thick core bases have been compared with 2DMCRT simulations and values of *s* have been inferred. These cases include interior ice, as well as ice from the surface layers in both bare and ponded conditions. Certain cores were then selected for full depth-resolved analysis.

RESULTS

In addition to the optical measurements, detailed measurements of the ice physical properties (e.g., temperature, salinity, and density profiles) were made (e.g., Fig. 1a) and photographs of the cores were

taken (Fig. 1b). These data and images show a surface layer which becomes less dense, more highly scattering, and has less structural integrity with time.

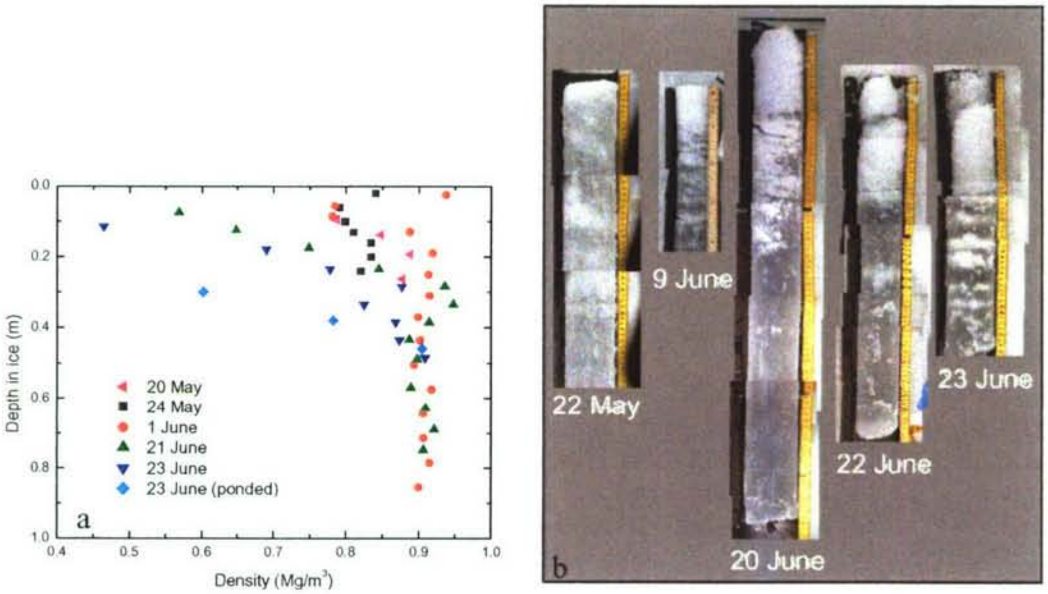

Figure 1 (a) Density as a function of depth in the ice for six days between 20 May and 23 June, (b) photographs of core samples taken in bare ice conditions between 22 May and 23 June. Each core has a brittle, bright white layer that features prominently near its top. This figure shows that the layer gets deeper with time.

Snow covered ice on 4 June

The core pictured in Fig. 2a was sampled on 4 June from under 2-3 cm of snow. Layers of low density ice at 0-5 cm, 10-15 cm, and 20 -25 cm depths show enhanced scattering. These increases in scattering are shown in the inferred scattering coefficient profile (Fig 2b). The profile is adjusted for an asymmetry parameter of $g = 0.94$ using the similarity relation. While the relative variations in the inferred scattering appear realistic, uncertainties in the magnitude of these coefficients are present due to questions about how to properly model the phase function of the scatterers in the ice.

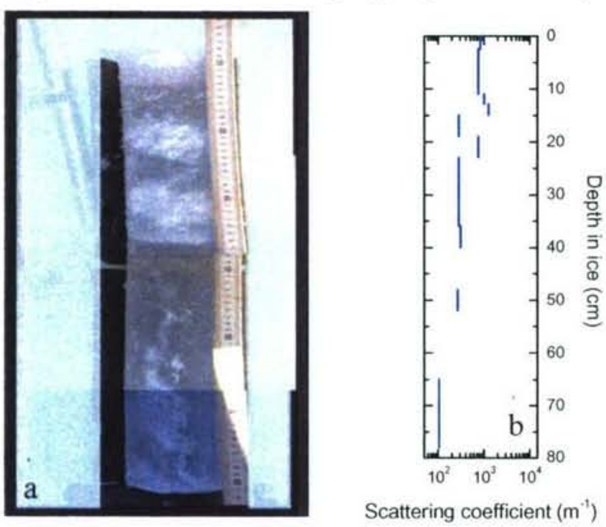

Figure 2. Core sampled from snow covered ice on 4 June, (a) photograph of core, and (b) inferred depth-dependent scattering coefficient.

Snow free ice on 4 June
The core pictured in Fig. 3a was sampled on 4 June from an area kept clear of snow for the previous 4 days. The core shows the initial development of a surface scattering layer. The increased scattering is shown in the inferred scattering coefficient profile (green lines, Fig 3b).

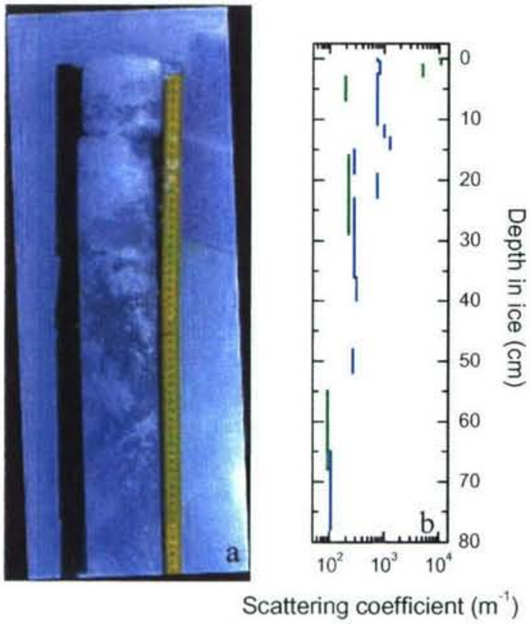

Figure 3. Core sampled in snow free area on 4 June, (a) picture of core, and (b) inferred depth-dependent scattering coefficient (green lines), shown in comparison with inferred scattering coefficients from snow covered area (Fig. 3b, blue lines).

Bare, melting ice on 21 June
The core shown in Fig. 4a was sampled on 21 June. The ice was bare and melting. The core shows an enhanced surface scattering layer. The layer is more strongly scattering and is deeper than the snow free case of 4 June. This increase in scattering is shown in the inferred scattering coefficient profile (Fig 4b).

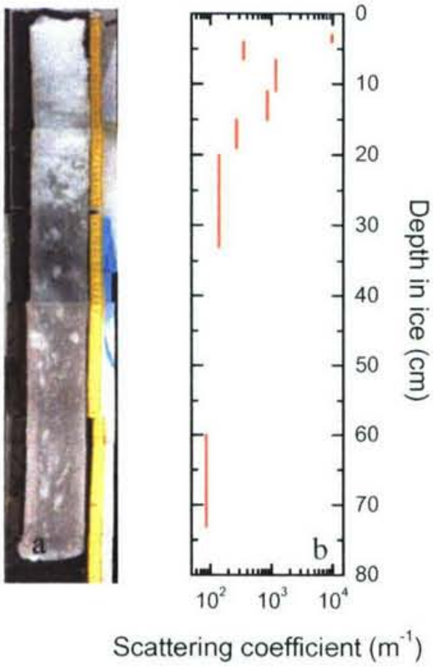

Figure 4. Core sampled from bare, melting ice on 21 June, (a) picture of core, and (b) inferred depth-dependent scattering coefficient.

Figure 5 shows inferred scattering coefficients (assuming $g = 0.94$) for ice in layers below 70, 50, 30, and 20 cm depth. The deepest interior ice (red squares and orange circles) has relatively constant scattering throughout the experiment. Values here generally are below 100 m^{-1}. Values increase towards the surface of the ice, but show no obvious trend with time.

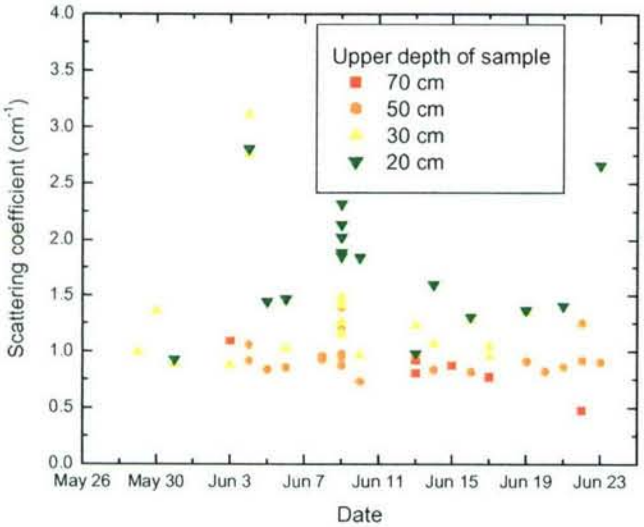

Figure 5. Plot of inferred scattering coefficient as a function of time for samples taken from bare sea ice.

Three broad concepts have emerged from this work: (i) a 3-layer structure for specifying the vertical variation of optical properties of both bare and ponded sea ice, (ii) the optical properties found in the ice interior are independent of time, and (iii) a picture of the evolution of scattering near the surface of bare and ponded ice as the melt season progresses. A generalized 3-layer structure for specifying the vertical variation of optical properties includes identification of a surface scattering layer (SSL),drained layer (DL), and interior ice. For bare ice, the SSL is generally the uppermost 5 -10 cm of the ice. The interior is everything below freeboard. The DL occupies the space between. This 3-layer structure can facilitate modeling radiative transfer in sea ice within large scale models. Clearly, differences in the transmittance of solar radiation to the ocean beneath bare and ponded ice derive from the presence or absence of a SSL and DL and the total ice thickness. This study found that scattering in the interior of the ice did not change with time. Comparisons with other studies looking at the optical properties of interior ice (*Light et al.*, in review) show similar behavior. A picture of how the optical properties of an ice cover progress as the surface undergoes the transition from bare to ponded is also emerging. The albedo of the ice drops precipitously as a thin pond forms. This drop in albedo requires additional shortwave energy to be absorbed within the surface layers of the ponded ice, which in turn, drives increases in scattering.

TRANSITIONS

The quantitative understanding developed from this study has benefited our conceptual picture of the role that sea ice plays in partitioning sunlight at the ocean surface. Results of this study have contributed substantially to the formulation used for a new radiative transfer parameterization in a global climate model (the Community Climate System Model, CCSM). Furthermore, these results will

facilitate the development of sampling strategies for the collection of more realistic spectral transmittance data under horizontally inhomogeneous ice covers.

RELATED PROJECTS

This work is relevant to two recently completed projects, "A new shortwave radiation parameterization for the CCSM sea ice model" (NSF ATM-0454311), and "Collaborative Research on observing the morphological and optical characteristics of the summer Arctic ice cover during the 2005 Trans-Arctic Expedition" (NSF ARC-0454900). During the first project, data from this project were used to develop a new parameterization for the optical properties of sea ice in a global climate model. During the second project, the optical core jacket was deployed in the laboratory on ice cores sampled during the cruise. Two ongoing projects, "Collaborative research on sunlight and the arctic atmosphere-ice-ocean system" (NSF ARC-0531026), and "Collaborative Research: Producing an Updated Synthesis of the Arctic's Marine Primary Production Regime and Its Controls" are benefiting directly from the work carried out in this project. Estimates of the amount of solar radiation penetrating the ice cover on a basin-wide scale are central to both these projects.

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